Flexibility offered to the distribution grid from households with a photovoltaic panel on their roof

Results and experiences from several pilots in a Norwegian research project

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Abstract— **The objective of this study is to evaluate how PV-oriented prosumers can offer flexibility to the Distribution System Operator (DSO). The different cases focus on the customer and changes on the customer side that will benefit both the customer and the distribution grid. (Actual tests of services delivered to the DSO have not been performed.) The study also highlights the importance of being proactive about the placement of roof top panels near the loads in the grid for a better balance between PV-output and loads at the terminal points in the grid. This approach demonstrated the secure operations of the grid well below the capacity limits and yield better rewards for the prosumer. In this study, storage options at the prosumer side are also considered and both technical and economic aspects are analysed. Special emphasis is placed on the impact of power tariff structures that include capacity considerations.**

Keywords—component; smart grid, flexibility, prosumers, photovoltaic (PV), battery, demand response

I. INTRODUCTION (*HEADING 1*)

This paper tries to answer two principal questions. In what way will distributed energy resources (DER) based on solar power create an impact on the electricity grid in Northern Europe, and in particular a country like Norway? The second question is what role prosumers with roof top photovoltaic (PV) panels can play?

A. Prosumers in Norway

Until 2013 the Norwegian market for PV panels was characterized by isolated installations operated in island mode, not connected to the power grid [1]. But the accumulated capacity has increased, and in 2015 a total of 2,45 MWp was installed, approximately 10% more than the volume installed in 2014 [2]. 11,4 MWp was installed in 2016, which is more than 366% the volume installed in 2015. Table 1 shows the development of total PV power capacity installed in Norway.

Table 1 Installed capacity [kWp] of PV panels in Norway [3]

	Up to 2012	2013	2014	2015	2016	Total
Installed capacity [kWp]	9952	620	2239	2450	11426	26687

B. Smart meters in Norway

In Norway, smart meters should be installed within 1st January 2019, and then all customers will get (at least) hourly metering of their electricity consumption. The regulations require that the new smart meters should be able to [4]:

- Store the meter data with a registration frequency of maximum 60 minutes, but it should be possible to change the registration frequency to a minimum of 15 minutes.
- Disconnect or reduce ("electrical fuse") the total load at the customer, except customers metered with a transformer (large customers).
- Meter both active and reactive power – in both directions (in/out).

Since the smart meters should be able to meter both active and reactive power, to and from the customer, the meters are already prepared if a customer wants to invest in a PV panel and become a prosumer. Additionally, the smart meters will be an enabling technology for new services and price incentives (grid tariffs) for the customers in the distribution grid.

C. FlexNett research project

FlexNett is an abbreviation for 'Flexibility in the future smart distribution grid' - a Norwegian research project (2015-2018). The project aims to contribute to an increased flexibility in the future smart distribution grid by demonstration and verification of technical and market based solutions. This paper presents results based on measurements from residential households and prosumers at demonstration sites, focusing on the role of prosumers (households with a PV panel on the roof).

II. METHOD OF APPROACH

A. Case oriented approach

The FlexNett project defined several case studies, each with a slightly different focus, and an empirical approach was adopted to investigate these. The common denominator was how prosumers can provide flexibility to avoid congestion and other capacity problems in the distribution grid. The case

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studies were conducted in different parts of Norway. The overall idea has been to determine regional differences and commonalities too. This relates to such things as solar height during the year. But it also pertains to different economical incentives. A few DSOs in Norway have introduced power grid tariffs, while most of the others charge households based on energy use alone. According to recent regulations feed-in of electricity, less than 100kW peak is exempt for any additional tariffs. The following cases are presented in this paper:

1. Prosumer with or without storage
2. Prosumers exposed to power grid tariff
3. Prosumers in neighbourhoods/regions with different locations of batteries

B. Data harvest

Data have been collected from smart meters, PV inverters and other sensors for 2,5 years. Hourly consumption and generation data have been collected from an extensive group of households in different parts of Norway. For reasons of privacy protection, the different records cannot be traced back to a specific address. The consumption data have been applied in simulations and used for analytical purposes. Some loads have been monitored specifically. Such loads include boilers and charger of electrical vehicles (EV). Generation from PVs have been monitored on a 10-minute basis and compared with hourly meter for import and export. For individual cases minute-by-minute records have been required. In addition to this, geographical records have been collected to determine the impact of topography and PV panel orientation.

C. Empirical analysis

To determine the impact of both individual and groups of households, field studies were conducted in one part. The density of PV based energy prosumers at Hvaler is relatively high. A selection of 25 prosumers were studied to determine their performance. All of them use the same type of solar panels (3,1 kWp) and inverters, and thus constitute a good reference case. By means of a geographical information system and field studies it was possible to determine a relationship between generation, panel orientation and location. The empirical study conducted was also used to compare estimates from existing generation models based on satellite data with actual production data. The same study made it possible to determine the impact different, local parameters have on production. These results were again compared with pertinent consumption data and used to determine the impact on the local infrastructure and the economic benefits each household could expect with the current tariff regime.

The other pilot location was a single-family house in the middle of Norway (Steinkjer). The house is heated by radiators and the hot water for this and the hot tap water come from a 300 liter, 3 phases 11.2 kW (divided on 4 different electric elements) hot water unit (HWU). The owner also has an electric vehicle, taking 2,2 kW when charging. The HWU and the electric vehicle are considered as flexible loads in this case. On the roof of the house, 12 PV panels, in total 3 kWp are mounted, directed against south with an elevation of 15^{0} (which is the angle of the roof). The PV-system is feeding energy into one phase inside the house. Equipment for metering of both the generation and consumption for specific appliances were installed at the customer.

III. CASE STUDIES

This section describes the three different case studies presented in this paper.

A. Case 1:Prosumer with or without storage

This case has focused on how a prosumer can improve the benefit from a PV-installation. The analysis is based on the prosumer, located in the middle of Norway. The starting point is the following relation for electric energy for a prosumer:

Consumption = Energy from grid + Produced – Energy to grid

Given a constant consumption, it is favourable for the prosumer to minimize the energy from the grid by maximize the production and minimize the energy delivered to the grid.

The house is equipped with a smart meter at the 3 phases grid connection point, giving hourly measurements of the energy floating in and out of the house. In addition, equipment for measuring effect and energy with 1 minute resolution are installed at each phase at the grid connection point, at each phase at the HWU, at the one phase of the electric vehicle charging point and at the one phase PV converter feeding point. The minutely measuring has going on in the period 5^{th} of July 2016 – 31^{st} of August 2017, see Table 2 and Figure 2.

Table 2 PV production 2016.07.05 – 2017.08.31

<table>
<tr><td></td><td colspan="6">2016</td><td colspan="8">2017</td></tr>
<tr><td>Month</td><td>July</td><td>Aug</td><td>Sept</td><td>Oct</td><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>Mar</td><td>April</td><td>May</td><td>June</td><td>July</td><td>Aug</td></tr>
<tr><td>Production [kWh]</td><td>313</td><td>307</td><td>174</td><td>143</td><td>11</td><td>1</td><td>0</td><td>7</td><td>82</td><td>269</td><td>371</td><td>360</td><td>371</td><td>280</td></tr>
<tr><td>Production [kWh]</td><td colspan="12">2040</td><td colspan="2">651</td></tr>
</table>

Imaging an envelope curve enclosing the measurements in Figure 2, it is obvious that the production tends to be zero in middle of November, for then to increase in start of February. The middle of this period is about 21^{st} of December, winter solstice. The explanation for this long period without PV production is due to the low elevation of the PV panel (15^{o}). Combined with the low solar elevation during mid-winter (see Figure 3) will the effective irradiance be very low. The low elevation of the panel will also ease the snow to cover the panel, which probably is the reason why the production in March is so low.

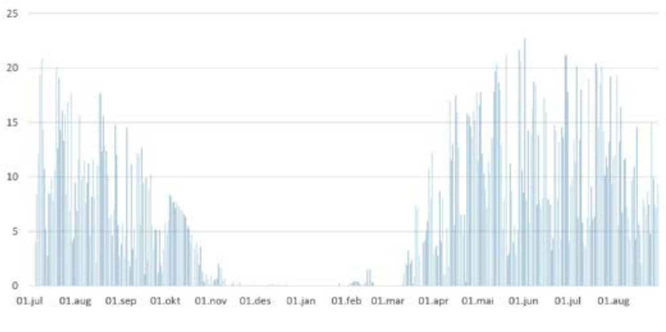

Figure 1 Daily PV production 2016.07.05 –2017.08.31 [kWh]

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Allow for the resulting angle between the sun beams and the PV face normal vector, it is possible to calculate the potential production based on the direct irradiance at different orientations of the panel. (The PV panel will also produce electricity at indirect irradiance, which is not included in the following.) In the following, the panel is directed against south.

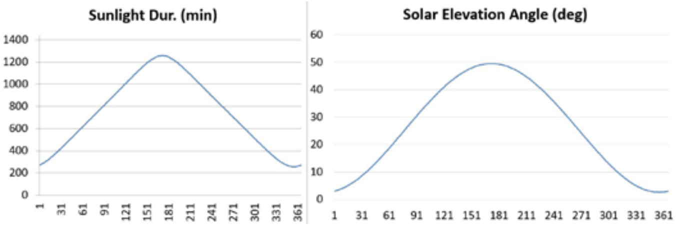

Figure 2 Sunlight duration (left) and solar elevation angle (right) at all days of 2016, as seen from the location of the PV panel [1]

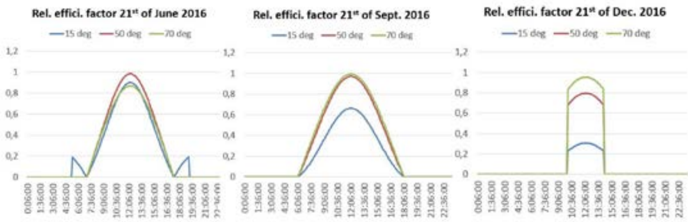

Figure 3 Relative efficiency factor of a PV panel at different days, using 15°, 50° and 70° elevation, panel pointing at south

Figure 4 shows the relative momentary production efficiency of a panel. The value "1" corresponds to optimal irradiance (coincident to the normal vector) and will at most happen once a day. (Be especially aware that the curves for 21st of September is wider than the curves for 21st of June.) The integral of a curve corresponds to the potential for production that day. These daily integrals for a period are illustrated in Figure 4.

The relations between the integral (i.e. potential for production) of the three curves 15°, 50° and 70° in Figure 5 are 1.00, 1.58, 1.67. Also notice how the elevation of the panel can shift the quantity of production to late autumn, when the energy is more needed.

Based on the relative efficiency factors the real measurements (Figure 2) are transformed to estimated production given other elevations on the PV panel. The relations between the real production at 15° and the estimated productions at 50° and 70° are 1.00, 1.39, 1.41.

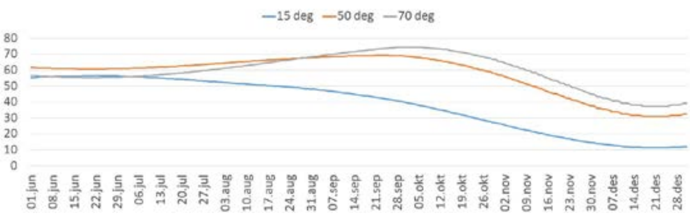

Figure 4 Total relative efficiency factor a day for a PV panel directed against south (2016.06.01 – 2016.12.31)

[1] Earth System Research Laboratory's web site https://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html

These productions are underestimated, as the real production mid-winter is zero (i.e. nothing to transform) and would most probably be different from zero at 50° and 70° elevation of the panel.

To see the potential for reducing energy fed into the grid, the production and consumption of the prosumer are analysed. Even though the energy taken from the grid is much higher than the production, energy is also fed into the grid in the same interval. This is true analysing on daily basis, roughly spoken on hourly basis, but definitively not true when analysing on minutely basis. Use of local energy storage could accumulate momentarily production surplus and by that prevent feeding energy into the grid. Because the consumption always is higher than the production on a daily basis, the storage does not need (for this purpose) to be larger than daily quantity of energy fed into the grid. As the consumption on the whole is for thermal use (the HWU), the storage might be stored as thermal energy. Figure 6 shows how energy is stored in the HWU.

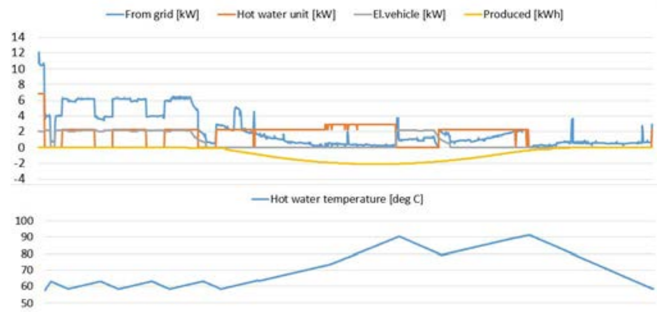

Figure 5 Simulated consumption data and hot water temperature, based on measurements from 18th Aug. 2016

This case has shown how a prosumer can increase its benefits from a PV-system. By choosing a well-founded orientation of the PV panel, the quantity and time-of-year of production can be adjusted. Further, to minimize the feeding of produced energy into the grid, it is illustrated how an already installed thermal storage (HWU) can be used as energy storage.

An electric battery was installed at the prosumer at the end of the project period. It was decided that the inverter connected to the battery in the beginning should be used for voltage support and balancing out the unbalances between the line voltages. Figure 7 shows the unbalance between the different phases (before starting the inverter) and reduced unbalance between the phases (after starting the inverter).

Figure 7 RMS voltage metered (Cycle by cycle), before and after the inverter connected to the battery was used for voltage support

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B. *Case 2: Prosumers exposed to power tariffs*

Case 2 overlapped Case 1 to some extent as it was important to establish mutual references. As pointed out for Case 1 issues related to the use of PV panels in the upper part of the northern hemisphere was also part of the investigations carried out in Case 2. But instead of addressing a specific household a full neighbourhood was studied.

The case study at Hvaler was supported by simulation system created for the purpose. The simulation system takes actual records or generated time series based on such as input. Both consumption data and generation data are included. The simulation is triggered by a random function, but once an initial context has been established, time series are generated through a forecasting process supported by a machine learning algorithm. A recursive neural network (RNN) has been trained on empirical data from the 25 sites monitored. Some noise has been added to generalize somewhat. Given a specific context (roof coordinates, date, capacities etc.) a time series compatible with the empirical material is generated. A GIS platform supports the simulation and holds information on properties, topography and site-specific characteristics. The user may select individual houses or groups of houses to explore different scenarios under relevant tariff regimes.

The residents in this area live in villas built in wood during the 1970-ies and with a typical Nordic architecture. Consumption varies between 20000-40000 kWh per year. A small number of the households have PV panels installed already. All of them are equipped with smart meters. Equally important, all of them are subject to grid tariff that consists of a fixed fee, an energy specific part and a power based part. The energy part has a unit cost of 0,3 eurocents/kWh. The power part demands €7,3 per kW per month for the average of the three highest peaks during the month. If that average is 4 kW all year the end-user is charged around €350 for use of that capacity. Consequently, self-consumption becomes attractive during peak hours. Regular households typically demonstrate a morning and afternoon peak. This implies that PV panels which are, by default, facing south tend to produce when consumption is low. This will cause surplus to be fed into the grid. Cumulative feeds are known to cause capacity problems and affect voltage and phase balance. With the existing power tariff it seemed reasonable to assume that PV installations should, if possible, be oriented in a more easterly or westerly direction to absorb the usual consumption peaks. This should level out loads and reduce capacity issues for the grid owner. It could also yield better economic benefits for the household. It could also provide increased justification for the introduction of a power based tariff. Moreover, it could possibly help to align the interests of the prosumer and the grid owner. Analyses based on empirical data as well as simulations were conducted for single houses with PV panels mounted on roofs facing different directions. An example based on metered values is shown in Figure 7 together with a typical "camel back" consumption as shown.

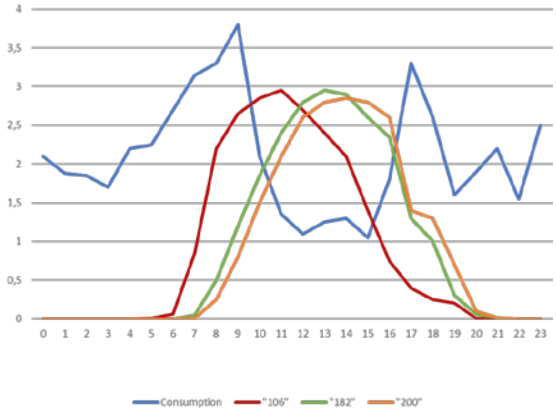

Figure 7 Generation profiles for PV panels on August 15, 2016. Y-axis shows kWh/h. One panel is mounted in an easterly direction (108 degrees). Another is facing south (182 degrees) and a third is facing more west (200 degrees). This is compared with arbitrary selected consumption profile.

The net production is almost the same. However, the panel facing south reduces the major peak. With a persistent pattern like this the owner of the PV panel facing south would make an economic gain 14-15% with the current power tariff compared to a standard south oriented installation. When the sun reaches zenith there are only minor differences in production. However, the curves in Figure 8 show when 1 kW is reached for a 3,1 kWp panel facing different directions in the morning and evening for different dates. On August 15 a panel mounted at 106, 182 and 222 degrees will reach 1 kW at 7:15, 8:30 and 9:55 respectively. On March 15 1 kW is reached at 9:15, 10 and 10;55 respectively.

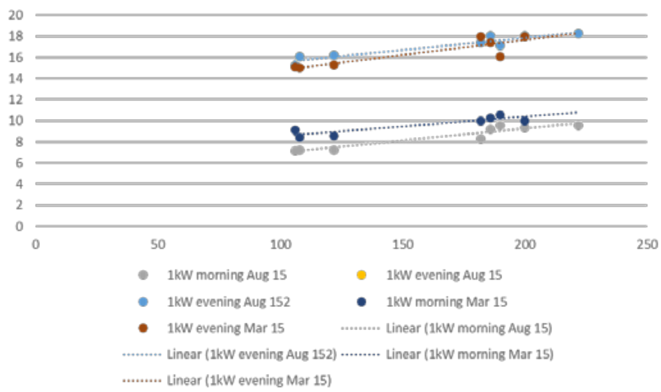

Figure 8 Empirical data showing when 1kW is reached for a 3,1 kWp panel facing different directions in the morning and evening on different dates.

Similar observations can be made for the evening. Simulations were carried out for a full year for two types of houses, one with a PV panel facing slightly east and one facing directly south, both with randomly picked consumption profiles with an average annual consumption of 15000 kWh. The expected economic consequences were calculated. Results are shown in Table 2. This shows the impact of the power part of the tariff.

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Table 2 Yield for a south oriented panel vs an east oriented

Degrees	PV panel capacity [kWp]	Annual yield [kWh]	Energy part of tariff (€)	Power part of tariff (€)	Sum variable tariff {€)
182	3,1	3320	287,1	355	622,2
106	3,1	2759	290,5	312	602,2

Table 2 shows average figures for multiple households of a certain size. The standard deviation may be significant. However, the statistical distribution for the peak hour in the morning tend to be skewed, suggesting that a greater part of the population start the day around 7:00 -7:30 a.m. with a long tail towards noon. The difference between the two orientations shown in Table 2 would increase if the base load related to electric space heating is reduced. The relative importance of temporary loads such as lights, boilers and other appliances, typically found in most homes, will increase. In regions where the thermal base load is fuelled by gas or oil the difference would be very significant. An increase in the electric base load is likely to reduce the difference. An increase in PV panel size would also favour the off-south solution. It should also be apparent that a higher power tariff relative to the energy part would favour an orientation that encourages self-consumption during peak hours. When running simulations for multiple households PV panels mounted more east would, for the same average pattern of consumption, absorb 60-80% of the cumulative morning peak. With this an issue arises with how to manage the evening peak. Three potential solutions are currently investigated. One is to install two sets of smaller panels in parallel, facing slightly east and west, rather than a single panel facing true south. The two other alternatives relate to storage as discussed under Case 1 and Case 3. With a single sided panel solution as shown above (e.g. 106 degrees) a battery would be able to absorb the second peak. The combined solution would require less battery capacity and fewer charging/discharging cycles. Obviously, the suggested solution is meant to manage excessive periods of feed-ins. During the winter months, consumption loads must be treated differently.

A power tariff as specified encourages self-consumption during peak hours. Self-consumption is good for both the prosumer and the grid company. Not all house owners may have the opportunity to choose the optimal orientation, but a choice between a large installation on the main roof and a smaller one on the garage top may be real. The garage mounted PV panel facing more east (or west) may provide a better investment case than the south oriented panel on the house itself. To achieve the benefits that this offers, under a power tariff regime, pro-activeness one behalf of the grid company is important. Based on the type of analyses conducted the grid company can provide advice to owners of existing houses and new-builders on what is most beneficial for them and the grid company. PV panels ought to be oriented and mounted according to the consumption profile of the household. Pro-activeness implies too that the grid company or someone on its behalf engage contractors and municipal authorities before the design of new neighbourhoods are concluded. A simulation tool like the one developed and the method applied here, will make it possible to gain early insight of the kind presented here and thus reduce or even avoid potential capacity problems.

C. Case 3: Prosumers in neighbourhoods/regions with different locations of batteries

Case 3 investigated how electricity consumption changes during the day and the year for typical household customers, how potential large power variations should be handled for customers with both consumption and generations (prosumers) and how an electric energy storage (battery) could contribute positively for the distribution grid – considering alternative locations and ownerships of storage system.

Based on hourly data from more than 100 households for nine years (2007-2015) the trends of peak of the year hourly consumptions and total yearly kWh consumptions are studied. The comparisons are performed using normalized values and they are also indexed for proper comparison. The results of the analysis show that the percentage increase of the yearly consumption and the peak hour consumption are growing at different rate (See Figure 9). Each year the percentage change of yearly consumption from 2007 value is increasing by 1.85% and by 2.89% for peak-hour.

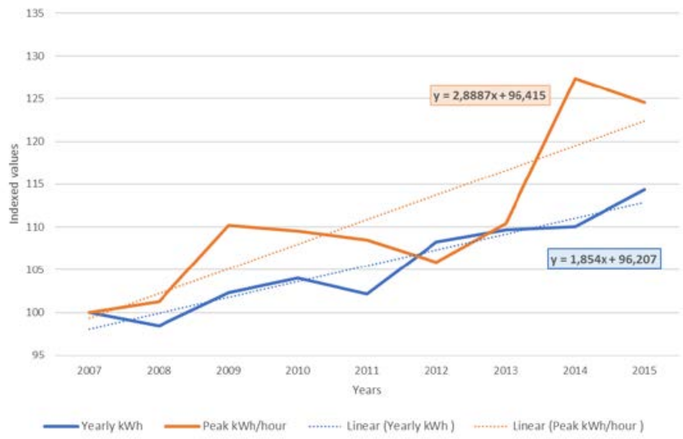

Figure 9 Comparison of the change in total normalized kWh yearly consumption with the change in the maximum hourly peak of the year for the normalized load between 2007 and 2015.

Based on the calculated trend in consumption and using a 3.0 kWp PV model, the load and generation under a MV/LV substation with 60 customers in 2025 are estimated (Figure 10).

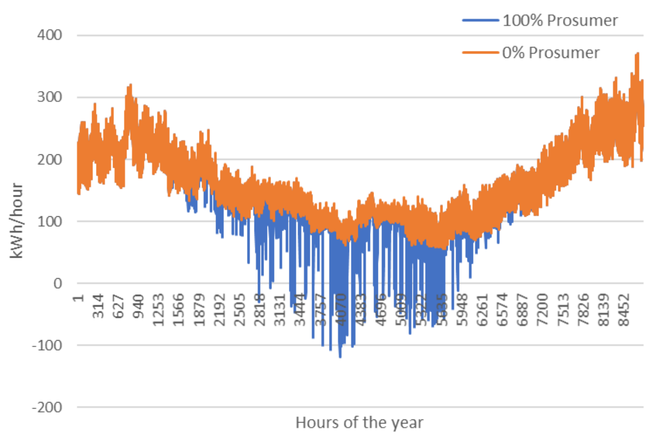

Figure 10 Load and generation under a MV/LV substation in 2025

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On year 2025 the secondary substation will be overloaded to up to 120% loading at the peak hour of the year considering the current load growth rate (305 hours in a year customers feed electricity into the grid for 100% prosumers)

The results show that without storage system, future integration of prosumers with PV will have no effect on the peak demand in the network. This attributes to the very poor correlation between the household consumption and the PV-generation in Norway (see Figure 11). However, with the current trend of load increment, the secondary substations are expected to experience overloads in winter although summertime reverse power flows will also increase.

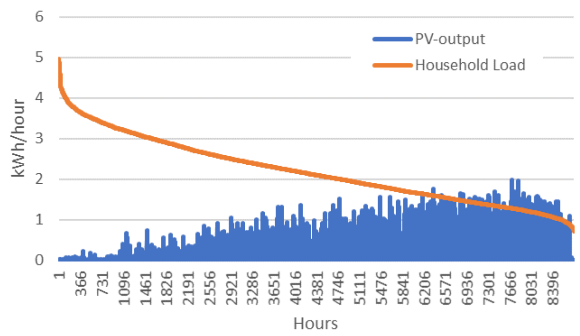

Figure 11 Duration curve representing the descending order of household load and the respective PV output [5]

Storage systems are essential together with PVs to reduce the peak loads. The potential by using storage elements at different locations and sizes are evaluated as an alternative to grid investments. The storage battery types analysed are:

1. Prosumer owned battery at household level (Size: small scale distributed)
2. Community owned (Size: medium scale)
3. Utility owned battery at MV/LV substation level (Size: large scale)

The three storage solutions are investigated for their impact on both the distribution grid and the self-consumption, based on meter data from a prosumer located in a weak distribution grid in Central Norway. As the results in the above three cases demonstrate, distributed energy storage systems at household level might be attractive solutions to reduce the size of the peak demand as seen by the distribution grid (see Figure 10).

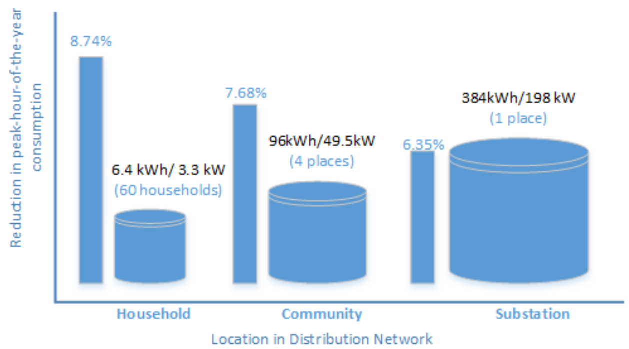

Figure 12 Different locations of storage system and their respective reduction potential of the peak load of the year [5]

IV. Conclusive Discussion

Case 1-3 show the impact of solar based prosumers in the northern part of Europe. It is evident that households can benefit from roof top panels. A poor correlation between consumption and PV-based electricity generation suggest measures to control feed-ins. At the same time, even small solar based feeds can help level consumption and balance out peaks for a major part of the year. Self-consumption is encouraged. Case 1 shows how a local solution for storage can support this objective. Power tariffs have been introduced to curb peak consumption. However, for prosumers this should be followed up by pro-active measures on behalf of the grid company as well as the prosumer himself. Orientation of PV panels to increase self-consumption during peak hours can be beneficial for both parties, as highlighted by Case 2. Case 3 studied the role of different battery types located with the individual prosumer or in more central locations. Future projections show that increased electricity consumption can cause a capacity problem. Distributed generation may be advantageous for the grid company if self-consumption can be encouraged. Large scale use of batteries associated with prosumers offer a good solution, but the economic prospects are currently not that attractive.

V. Acknowledgment

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